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EXPERIMENTAL STUDY OF EFFECT OF SIMULATED REACTOR CORE POSITION ON NOZZLE HEAT TRANSFER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

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A simulated reactor core was installed at various positions upstream of a conical nozzle in order to determine the influence of core position on nozzle heat-transfer and boundary-layer characteristics. The tests were conducted in an air facility at a nominal stagnation temperature and pressure of 970° R and 300 pounds per square inch, respectively.

author

INTRODUCTION

In recent years the nuclear rocket has received widespread interest as a propulsion device for long-term ambitious space missions. Many problems, however, have been encountered in the development of a workable engine (refs. 1 to 3). In addition to the problems associated with the reactor, it has been shown that the rocket engine may have a marginal cooling capability (ref. 4) because of the high heat fluxes in the throat region.

The existence of this throat cooling problem requires an accurate assessment of nozzle heat-transfer rates; however, to date, the most sophisticated prediction techniques are not precise enough for the gas side of the nozzle. Gas-side estimates are complicated by turbulence induced in the flow from the reactor core. Data from references 5 and 6 indicated a sensitivity of nozzle heat transfer to changes in the position of a reactor core simulator.

The present investigation was conducted in order to study, in greater detail, the influence of core position on the nozzle heat-transfer and boundary-layer characteristics.

SYMBOLS

D_{th} nozzle throat diameter

h_i heat-transfer coefficient based on enthalpy

i enthalpy

P pressure

Pr Prandtl number

q heat-transfer rate

T temperature

u velocity

x axial coordinate measured from nozzle throat

y distance normal to wall

ρ density

Subscripts:

ad adiabatic

e edge of boundary layer

s static condition

t local stagnation condition

w wall condition

0 reservoir condition

APPARATUS AND PROCEDURE

The heat-transfer facility, boundary-layer probes, and heat-flux meters used in this investigation are described in detail in reference 6; however, a condensed description of the apparatus will be presented herein for purposes of clarity.

The heat-transfer facility is shown schematically in figure 1. The basic configuration consisted of a 6.5-inch-inside-diameter by 17-inch-long adiabatic cylindrical approach section followed by a water-cooled 30° convergent, 15° divergent conical nozzle. A plenum boundary-layer bleed system was used to effect a uniform velocity profile in the plane of the inlet leading edge. The working fluid was air heated to a nominal temperature of 970° R at a pressure of about 300 pounds per square inch absolute.

A simulated reactor core, having 0.25-inch-diameter holes with a center-line spacing of 0.5 inch, was installed in three locations upstream of the cylindrical inlet. These positions were (1) at the nozzle entrance, (2) 1 inch

upstream of the nozzle entrance (0.15 core diameter), and (3) 3 inches upstream of the cylindrical inlet (20 in. or 3.1 core diameters upstream of the nozzle entrance).

Heat-transfer rates were measured at 19 stations in the nozzle by means of steady-state-conduction heat-flux meters. Heat-transfer coefficients based on enthalpy were computed from the measured heat-transfer rates with the following equation:

$$h_i = \frac{q}{i_{ad} - i_w}$$

where the adiabatic wall enthalpy i_{ad} is given by

$$i_{ad} = i_s + Pr^{1/3}(i_0 - i_s)$$

A Prandtl number of 0.7 was assumed.

Boundary-layer kinetic head measurements were obtained with a Pitot probe having a rectangular opening 0.002 inch high by 0.030 inch wide. The probe was located normal to the wall at a station in the convergent part of the nozzle corresponding to a Mach number of 0.08.

The kinetic head measurements were converted to velocities by means of the incompressible Bernoulli equation

$$P_t - P_s = \frac{1}{2} \rho u^2$$

The density at any point in the boundary layer was computed from the wall static pressure and the corresponding value of measured total temperature with the assumption that $T_s/T_t = 1.0$. This latter assumption is valid since the Mach number of the measuring station is low (Mach number, 0.08).

Boundary-layer temperatures in the nozzle station were measured with a probe containing a bare junction Chromel-Alumel thermocouple. The diameter of the junction was 0.005 inch. The reference temperature for the probe was obtained from a thermocouple in the plenum.

RESULTS

The nozzle heat-transfer coefficients h_i are plotted as a function of axial distance x/D_{th} in figure 2. The distributions represent the three cases of the simulated reactor core located upstream of the nozzle and the case in which the core was removed.

Location of the core 3 inches upstream of the cylindrical approach section (approximately 3.1 core diameters ahead of the nozzle entrance) resulted in a heat-transfer distribution nearly identical to that obtained with the core

removed. Turbulence measurements relevant to this latter observation are discussed in reference 6. The measurements revealed that an appreciable reduction in turbulence level had occurred between the core and the measuring station in the convergent part of the nozzle, which might explain the negligible effect on nozzle heat-transfer coefficients.

When the core was located at the nozzle entrance and 0.15 core diameter upstream, throat heat-transfer coefficients were about 28 percent higher than values obtained with the core removed. Equally significant was the heat-transfer distribution in the convergent section of the nozzle with the reactor core simulator located at the nozzle entrance. For this location of the core, the heat-transfer coefficient h_i at the first measuring station in the nozzle was nearly as high as the throat value (see fig. 2). However, the high heat-transfer coefficient at this first measuring station was reduced 37 percent by moving the core simulator 0.15 core diameter upstream of the nozzle entrance. At the third measuring station the heat-transfer coefficient was reduced by approximately 50 percent with this 0.15-diameter displacement of the core. This pronounced heat-transfer reduction in the convergent part of the nozzle suggests that reactor design criteria include a moderate separation of the core and nozzle.

The third heat-transfer measuring station in the nozzle ($x/D_{th} = -1.68$) is of special interest because the boundary-layer temperatures and velocity profiles are also measured at this location. At first, the large difference in the heat-transfer coefficient at this third measuring station was expected to be adequately explained by the measured boundary-layer temperature and velocity profiles, shown in figures 3 and 4, respectively. However, the temperature and velocity profiles at this third measuring station are almost identical for the cases of no core and a core located at the nozzle entrance. If the boundary-layer profiles and the measured heat transfer are correct, the large differences in the heat transfer may possibly be attributed to effects in the sublayer region near the wall that cannot be measured. With the core moved 0.15 core diameter upstream of the nozzle entrance, the slope of the temperature profile (fig. 4) steepened, which indicated greater heat transfer than with the core at the nozzle entrance. This temperature profile is disturbing since the measured heat transfer is significantly less (fig. 2) as the core is moved 0.15 core diameter upstream of the nozzle entrance. However, the sublayer region near the wall may still control the important heat-transfer mechanism, while a slight change in the temperature profile may be only a secondary effect on the heat transfer. The measured boundary-layer profiles for each core location retain the general similarity which is characteristic of profiles obtained in the accelerating flow field of the nozzle (ref. 6).

Experimentally, it may be possible that axial changes in core position produced differences in the orientation of the peripheral core similator holes relative to the temperature and pressure probes. Thus, there is a possibility that jet impingement phenomena are not entirely eradicated by acceleration effects by the time the flow reaches the boundary-layer measuring station. However, as an indication of extreme acceleration effects, unreported recent experimental data have shown that a fully developed turbulent boundary layer entering the present nozzle is reduced to approximately the same value of

boundary-layer thickness as reported herein at the same measuring station.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the effect of simulated reactor core position on nozzle heat-transfer and boundary-layer characteristics, and the following results were obtained:

1. The inclusion of a simulated reactor core upstream of a conical nozzle may or may not influence nozzle heat-transfer coefficients, depending on the relative positions of the core and nozzle. When the core was located at the nozzle entrance and 0.15 core diameter (about 1.0 in.) upstream, a 28-percent increase in throat values of heat-transfer coefficient was realized, compared to the case of no core. When the core was displaced about 3.1 diameters ahead of the nozzle entrance, the heat-transfer coefficients were virtually the same as values obtained with the core removed.

2. When the core was located at the nozzle entrance, heat-transfer coefficients in the entrance region (first measuring station) were nearly as high as throat values. This observation is significant for it indicates a potential compounding of the difficult nozzle cooling problems.

3. At the first measuring station, the heat-transfer coefficient was reduced by 37 percent when the core was moved from the nozzle entrance to a position 0.15 diameter upstream of the nozzle entrance. The heat-transfer coefficient at the third measuring station was reduced by about 50 percent when the core was 0.15 diameter upstream of the entrance.

4. In the design of nuclear reactor systems, it may be desirable to incorporate a moderate separation of the core and nozzle in order to reduce the heat-transfer coefficients in the convergent part of the nozzle, especially in the region near the core interface.

5. Boundary-layer temperature and velocity profiles in the nozzle were quite similar for all core simulator positions even though heat-transfer rates at the survey station differed appreciably. This result suggests a possible predominant influence of the unmeasured sublayer region on heat-transfer rates.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 3, 1965.

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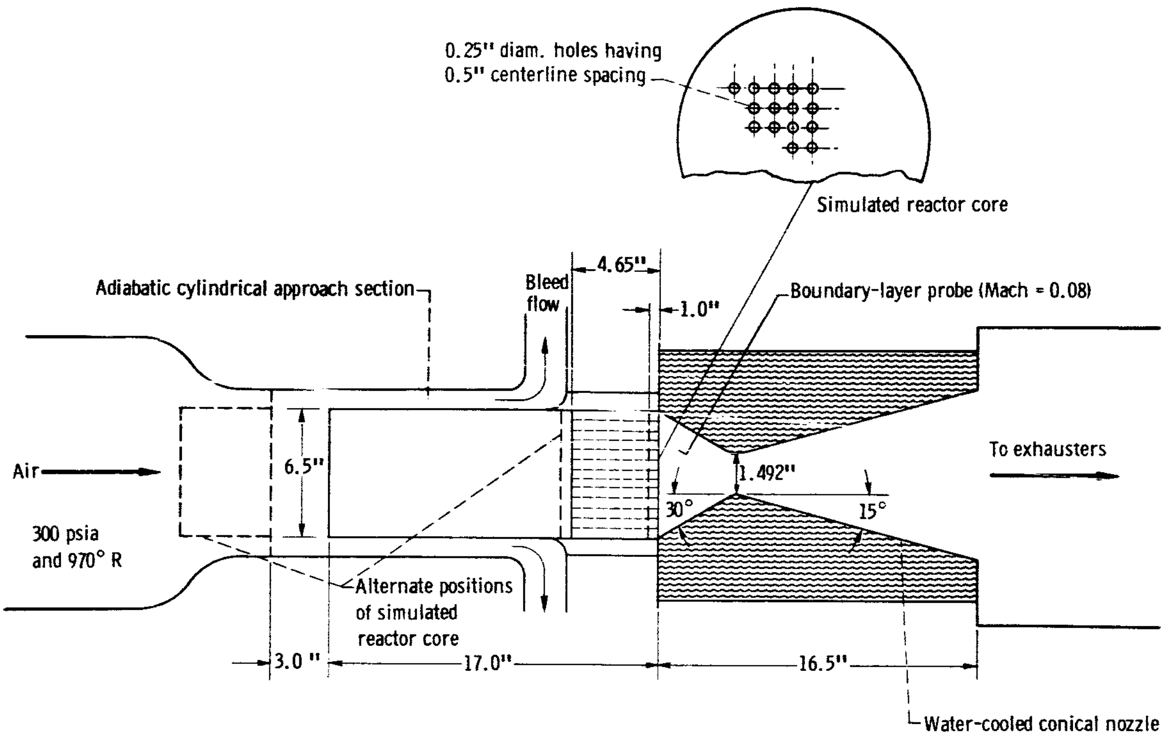

Figure 1. - Heat-transfer facility.

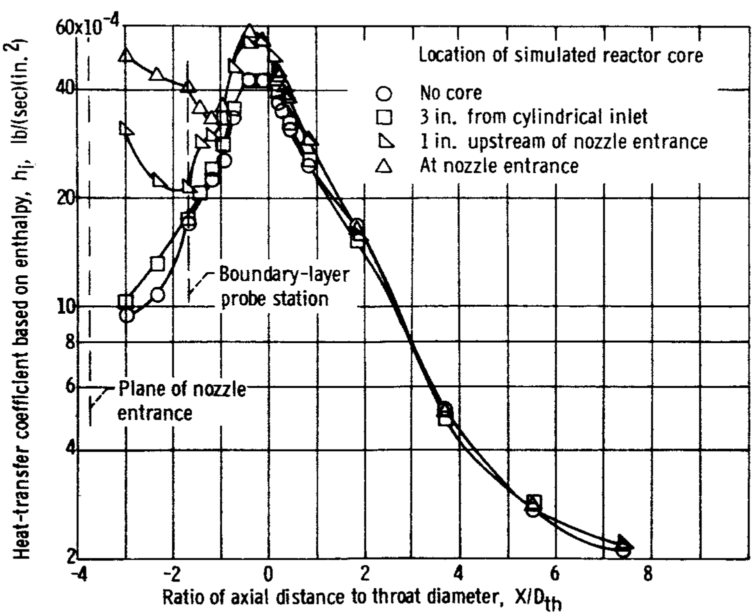

Figure 2. - Variation of heat-transfer coefficient along nozzle for various locations of simulated reactor core. Reservoir temperature, 970° R; reservoir pressure, 300 pounds per square inch; throat diameter, 1.492 inches.

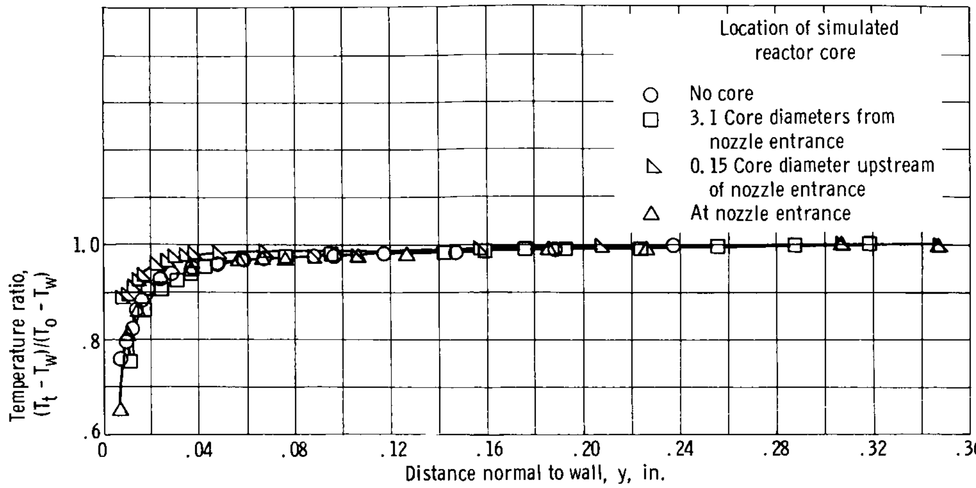

Figure 3. - Temperature profiles at convergent nozzle probing station for various locations of simulated reactor core. Reservoir temperature, 970° R; reservoir pressure, 300 pounds per square inch absolute.

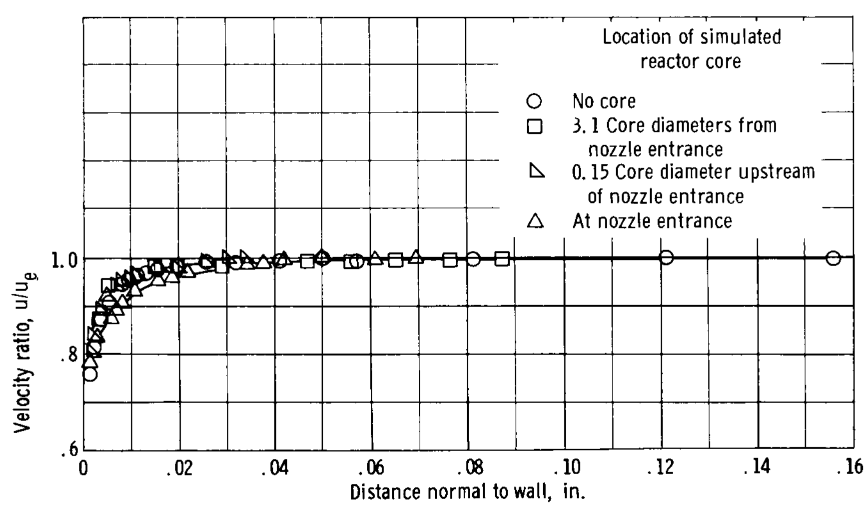

Figure 4. - Velocity profiles at convergent nozzle probing station for various locations of simulated reactor core. Reservoir temperature, 970° R; reservoir pressure, 300 pounds per square inch absolute.

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